Sub Topic: IC Engines, Gas Turbines, and Rockets

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# Impact of Flame-Wall Interactions on Combustor Liner Heat Flux

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**Abstract:** Heat transfer in gas turbine combustors is complicated due to the the widely changing flow features as well as the varying heat transfer due to the products of combustion (water vapor, carbon dioxide, and soot). By measuring total and radiative heat flux to the wall, we seek to better understand the impacts of the combustion process on combustor liners. Using a backward-facing step combustor, simultaneous heat flux and OH planar laser-induced florescence (OH-PLIF) measurements will provide information about the impact of flame-wall interaction on total and radiative heat flux to the wall. These quantities were evaluated in three different parts of the flow: the recirculation zone, the shear layer impingement region, and the boundary layer recovery region. Both total and radiative heat flux were shown to be dependent on Reynolds number and location in the flow. Initial analysis of OH-PLIF images shows a strong correlation between flame-wall interaction and higher heat flux measurements.
***Keywords:* Combustor liner, Heat transfer, Flame-wall interaction**

## 1. Introduction

Gas turbine engines rely on highly turbulent flows to stabilize the flame under high bulk velocities and lean premixed conditions. As emissions standards become more stringent, continual understanding in flame stabilization and behavior is imperative for proper design of combustor liners. Backward-facing step combustors have been used to study flame dynamics due to the nominally two-dimensional flow, high optical access and non-proprietary geometry [1–3]. Additionally, backward-facing step flows hold many of the key flow parameters of gas turbine engines (recirculation, shear-layer wall impingement, and boundary layer recovery) [4], as shown in Figure 1. Using a backward-facing step combustor, we seek to characterize the flame-wall interactions of a natural gas flame to compare against heat flux measurements made with OH planar laser-induced florescence (OH-PLIF) and heat flux sensors, respectively.

## 2. Experimental Methods

The backward-facing step combustor has been previously used to make heat flux measurements of vitiated flows [5] as well as for a flame stabilized off the backward-facing step [6]. It was designed with methods consistent with other experiments [4]. A schematic of the experiment is shown in Figure 2. A hydrogen igniter is used to establish a diffusion flame, and natural gas is premixed into

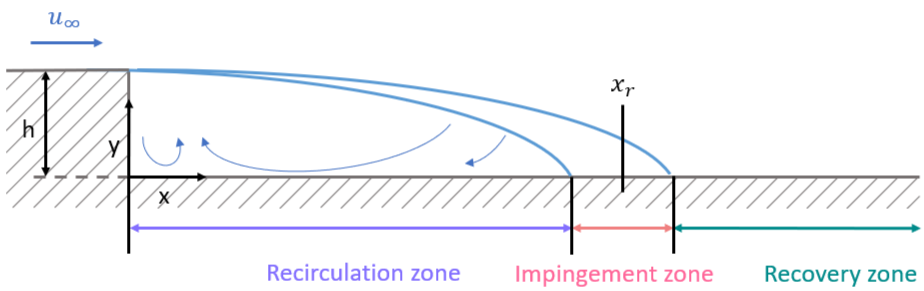


Figure 1: Schematic of flow behind a backward-facing step.

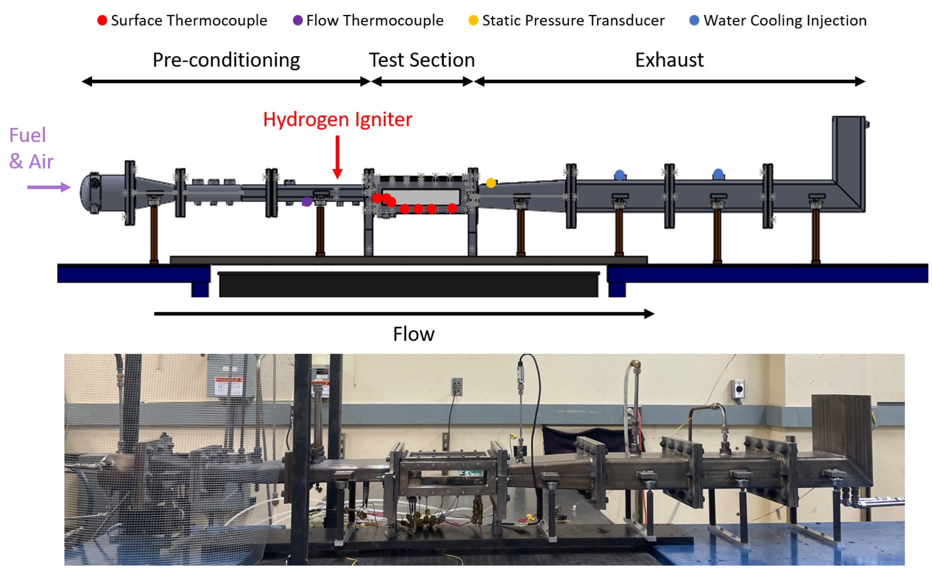


Figure 2: Schematic of experiment showing flow path and instrumentation.

the air flow until the flame anchors off the step. At this point the igniter is turned off and the flame continues anchored on the step.

Previous work showed relatively narrow range of operation [6], so a constant equivalence ratio of approximately 0.55 was tested. Reynolds numbers, $Re_h$, between 4199 and 8413 were tested and data were collected at plate temperatures, $T_{plate}$, between 348 K and 498 K. The plate temperature was monitored with thermocouples embedded in the bottom of the combustor 1/16" below the surface. Heat flux measurements were collected through the combustor using two sensors: a heat flux sensor and a radiometer. The heat flux sensor measures all incoming convective and radiative (total) heat transfer over a 180° field of view, where the radiometer has a sapphire window on top that only allows radiation between the wavelengths of 0.3-5$\mu$m, and a field of view limited to 150°.

The flame is imaged using high-speed OH-PLIF. An Edgewave Nd:YAG laser pumped a Sirah Credo dye laser, producing a laser wavelength of approximately 283.545nm. This was passed through a series of mirrors and a LaVision sheet forming optic to create a laser sheet approximately 20 mm wide, which was aligned with the center plane of the experiment and moved throughout

Table 1: Test matrix for heat transfer experiments.

| Condition Number | $Re_h$ | $\phi$ | $T_{ad}$ $[K]$ | $T_{plate}$ $[K]$ |
|---|---|---|---|---|
| 37 | 4199 | 0.54 | 1559 | 348, 423, 498 |
| 38 | 5249 | 0.54 | 1559 | |
| 39 | 6299 | 0.55 | 1578 | |
| 40 | 6823 | 0.55 | 1578 | |
| 41 | 7350 | 0.55 | 1578 | |
| 42 | 8413 | 0.57 | 1615 | |

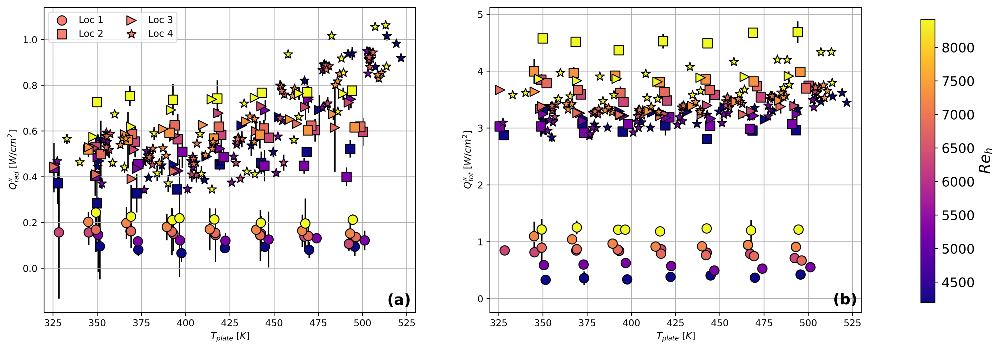


Figure 3: (a) Radiative heat flux versus plate temperature, $T_{plate}$ and (b) total heat flux as a function of plate temperature, Reynolds number($Re_h$) in the color axis.

the combustor to complete imaging through the combustor. A high-speed camera (Photron FASTCAM SA1.1) and LaVision high-speed intensifier were used for OH-PLIF. A filter with a center wavelength of 320 nm is used to isolate the signal from the OH radicals at 10 kHz for one second. Image acquisition was completed using the LaVision software package DaVis 8.

### 2.1 Results

Heat flux data was taken at three locations through the combustor: in the recirculation zone (loc 1), the impingement region (loc 2), and in the boundary layer recovery regime (loc 3 and 4). Figure 3 shows the measured radiative and total heat flux through the combustor. Several major trends are evident. First, the recirculation zone (location 1) has much lower heat flux than any other location, a result of the slow-moving fluid above the wall and the relatively low concentration of combustion products radiative directly above that region. Second, the total heat flux is much greater than the radiative heat flux. This result speaks to the impacts of radiative heat flux falling outside the wavelength range of the radiometer or convection. Lastly, the heat flux is mostly independent of plate temperature. The increase in heat flux in location 4 with temperature is due to the increase in temperature of the exhaust downstream of the test section. To heat the plate, the combustor is continually run; the longer the experiment is on, the hotter the exhaust gets and the more it radiates. Only the sensors in location 4 have a view to the exhaust, resulting in a bias in those measurements.

OH-PLIF imaging was also collected for comparison against the heat flux measured. 10,000 images were collected at each location. Figure 4 shows a schematic of the planes of view used in the imaging. The images will be first smoothed to alleviate the effects of noise in the camera and

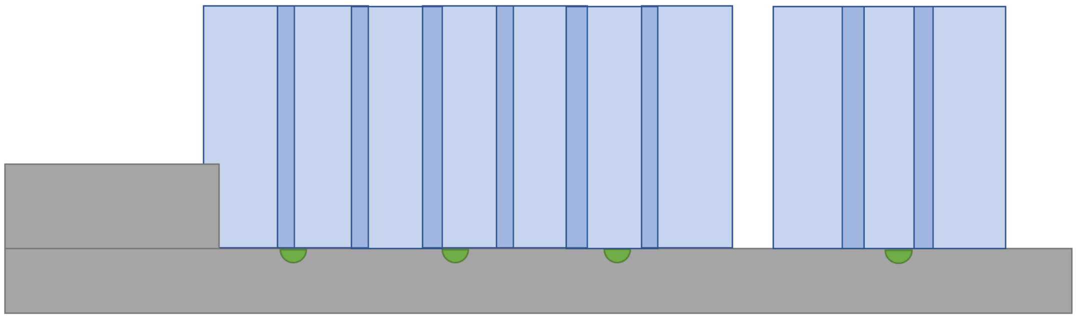

Figure 4: Schematic of the PLIF image sheet locations. Green half circles indicate the location of the sensors, and blue rectangles represent the approximate location of the laser sheets through the combustor.

intensifier using the medfilt2 in MATLAB. The smoothed images will be searched over for intensity that was above the background by a 300% threshold. The background noise was calculated from the images themselves. The increase in intensity is caused by the presence of OH fluorescing, thus causing signal. To statistically evaluate how often a flame was at each location, the intensity was treated as a bianary: if signal existed, the location was turned to a one and if not it was turned to zero. These images were then all averaged to calculate the time-averaged progress variable zero indicates a region with reactants and one is products.

## 3. Conclusions

Simultaneous heat flux measurements and OH-PLIF images were taken in a backward-facing step combustor to determine the impact of flame brush on heat flux measurements. Both total and radiative heat flux measurements showed dependency on Reynolds number but very little on plate temperature. Progress variable calculations will be performed to understand the extent of combustion effect on heat flux measurements. Understanding the impact of flame brush on heat flux to the wall in combustor liners will assist in more robust design of future gas turbine combustor liners.

## 4. Acknowledgements

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